

ARM PROGRESS REPORT - JULY, 2000 - RICHARD C. J. SOMERVILLE

1. Principal Investigator

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2. Title of Research Grant

“Single-Column Modeling GCM Parameterizations and ARM Data”

3. Scientific Goal(s) of Research Grant

This project focuses on the use of ARM data to improve the parameterization of cloud-radiation interactions and related physical processes in global and regional climate models. The work has several major components:

- Evaluation and improvement of parameterizations with ARM data using single-column models (SCMs) diagnostically to make direct comparisons of results from parameterizations with ARM observations;
- Testing of the parameterizations in global atmospheric models to determine the sensitivity of model results to all aspects of the physical parameterizations;
- Utilization of stochastic radiative transfer theory to develop parametric representations of cloud-radiation interactions and closely related processes for atmospheric models;
- Collaboration with the cloud physics and radiation group headed by Greg McFarquhar and Andy Heymsfield at NCAR to develop improved parameterizations of cirrus initiation, development and radiative properties for tropical and continental clouds;
- Collaboration with Dave Mitchell at Desert Research Institute. Mitchell has developed expressions for cirrus particle fall speeds that will be the basis for the microphysics model which he plans to supply us for SCM testing.

4. *Accomplishments in the previous twelve months*

- Single-column model parameterizations, especially those involving convection have been shown to be quite sensitive to model vertical resolution.
- Ground-based data from the ARM Southern Great Plains (SGP) site can be used to characterize the geometry of low-level, broken cloud fields and is suitable to be ingested into a 3D radiative transfer code.
- A stochastic, shortwave, radiative transfer model is being investigated as a new approach to representing the influence of cloud geometry and spacing on the radiation field. The stochastic shortwave radiative transfer model produces significantly different radiation fields from a standard plane-parallel model, however both models demonstrate sensitivity to the representation of cloud microphysics.
- Observational data collected during TOGA-COARE were used to force and constrain a SCM over the IFA region for 3 time periods totaling 78 days. SCM results successfully reproduced most of the temporal variability seen in the observed radiative fluxes, cloud amount and precipitation.
- SCM cloud amounts and radiative fluxes were more realistic when using a prognostic cloud/cloud water scheme than a diagnostic cloud scheme.
- Vertical cloud distribution became more realistic as more comprehensive cloud microphysics were included in the SCM cloud-radiation parameterization package.
- SCM results indicated that both shortwave and longwave radiative fluxes are sensitive ($\sim 20\text{--}30 \text{ W m}^{-2}$) to the parameterization of cloud ice particle radius.
- A comparison of eleven SCM simulations revealed common signatures identifiable as products of errors in the boundary conditions, while some intermodel differences have led to corrections or improvements in individual models.
- Results from perturbation experiments indicated that SCM results are sensitive to perturbations in the initial profiles of T and q representative of typical instrument and measurement errors and suggest that an ensemble of SCM runs should be performed for sensitivity studies or parameterization development.

5. *Progress and accomplishments during last twelve months (or from beginning of the current effort whichever is shorter).*

SENSITIVITY OF CLOUD-RADIATION PARAMETERIZATIONS TO VERTICAL RESOLUTION

An SCM is used to examine the sensitivities inherent in cloud-radiation parameterizations. Results include time-averaged output of radiative quantities such as downwelling shortwave radiation, outgoing longwave radiation, and cloud amount. Time-series of cloud amount, convective mass-flux, and planetary boundary-layer depth are used to investigate the demonstrated sensitivity of the cloud parameterizations to vertical resolution. When possible, evaluation of these quantities is made using observations from the ARM's SGP site.

The SCM displays marked sensitivity to changes in vertical resolution, especially in the calculation of convective cloud amount and outgoing longwave radiation. This is apparent in all of the model variables examined. The sensitivity, which is mostly related to the shallow convection algorithm, can change the average convective cloud fraction by as much as 20% over the range of resolutions tested, a substantial amount when compared to the typical observed value of cloud fraction, which is about 50%. The outgoing longwave radiation is modified by an average of 15 W m⁻², which is of the order of 5% or 10% of the observed value. Even stronger sensitivities are seen if the model pressure-layer spacing is modified. The DWSR variation is somewhat smaller than the OLR change but is still significant. Furthermore, the model results have not converged even at a resolution of 60 layers, and there are significant systematic differences between model results and observations.

It is unlikely that the strong sensitivity to vertical resolution apparent in these results is limited to the particular location, season, choice of parameterization, or other specific details of this study. Instead, it seems probable that contemporary general circulation models taken as a class contain parameterizations of physical process that tend to display the characteristics shown in this study, including a strong sensitivity to vertical resolution, systematic errors relative to observations, and a failure to converge to a well-defined limit as vertical resolution is increased, at least within a range of typical resolutions. An objective of future research is to produce parameterizations that are physically more realistic and numerically better behaved than those of

present-day climate models. In pursuing this objective, diagnostic tools such as the single-column model, in conjunction with observational programs such as ARM, will have an important role to play in developing and evaluating these parameterizations.

CHARACTERIZATION AND MODELING OF BROKEN CLOUD FIELDS

Three types of broken cloud fields are statistically characterized using daily observations from the ARM SGP measurement site, and the information is then ingested into a stochastic radiative transfer model. Each cloud type is identified by a representative cloud base height, cloud top height, cloud water path, particle effective radius, cloud fraction, and cloud horizontal scale. Data from the ARM SGP site can be used to provide the necessary information about the geometry of the cloud field for input into shortwave radiation routines. However, there is still improvement needed in some observations, such as that of cloud fraction and liquid water path.

Stochastic radiative transfer is investigated as a method of improving cloud-radiation parameterizations by incorporating the effects of cloud size and spatial distribution. The predictions of two shortwave radiative transfer models have been compared to observations from the ARM's SGP site for 5 days when fair weather cumulus clouds were present. One model is representative of the type of shortwave radiation parameterizations found in modern general circulation models. The other model is a stochastic radiation code that calculates the average radiation intensity field from statistically represented cloud properties. The input for both models was taken from measurements made at the ARM SGP site. Both radiative-transfer models can be used to predict the domain-averaged radiation field for a partial day. In comparison to observations from the Oklahoma Mesonet, the plane-parallel model does a better job predicting the downwelling shortwave radiation than the stochastic model. For cloud fields where the horizontal fraction is between 5% and 80% and the cloud thickness is approximately 1 km, the average difference in the predicted value of downwelling shortwave radiation at the surface between the two shortwave models averages 150 W m^{-2} . Both models are sensitive to the observed microphysical properties. The predicted values of downwelling shortwave radiation at the surface that are too low in both models relative to observations were probably due to large, non-physical, cloud optical depths.

The stochastic model offers a promising approach to representing radiative transfer through broken cloud fields, as it uses a more physically realistic description of the macroscopic

properties of the clouds. The described simulations are the first stage in the verification of the stochastic technique with real atmospheric data. The ultimate goal of this type of research is to develop a correction to a general circulation model parameterization that accounts for the influence of the cloud field geometry on the radiation field. To achieve this, additional observational data for varying cloud types, especially microphysical measurements, are required to refine the stochastic approach and improve its accuracy.

IMPLICATIONS OF MICROPHYSICS FOR CLOUD-RADIATION PARAMETERIZATIONS

An SCM and observational data collected during TOGA-COARE were used to investigate the sensitivity of model-produced cloud properties and radiative fluxes to the representation of cloud microphysics in the cloud-radiation parameterizations. Four 78-day SCM numerical experiments were conducted for the atmospheric column overlying the COARE Intensive Flux Array (IFA). Each SCM experiment used a different cloud-radiation parameterization with a different representation of cloud microphysics. All the SCM experiments successfully reproduced most of the temporal variability seen in the observed radiative fluxes, cloud amount and precipitation. The SCM model runs that calculated cloud amount as a function of cloud liquid water, instead of using a relative humidity-based cloud scheme, produced smaller amounts of both low and deep convective clouds. Additionally, larger high (cirrus) cloud emissivities were obtained with interactive cloud liquid water schemes than with the relative humidity-based scheme. Surprisingly, calculating cloud optical properties as a function of cloud liquid water amount, instead of parameterizing them based on temperature, humidity and pressure, resulted in relatively little change in radiative fluxes. However, model radiative fluxes were sensitive to the specification of the effective cloud droplet radius. Optically thicker low clouds and optically thinner high clouds were produced when an interactive effective cloud droplet radius scheme was used instead of specifying a constant value. Comparison of model results to surface and satellite observations revealed that model experiments, which calculated cloud properties as a function of cloud liquid water, produced more realistic cloud amounts and radiative fluxes. The percentage of occurrence of various cloud types from two SCM runs was compared to a climatology based on satellite measurements in the Tropical Western Pacific. The most realistic vertical distribution of clouds was obtained from the SCM experiment which included the most complete representation of cloud microphysics.

SENSITIVITY OF SCM RESULTS TO PERTURBATION OF INITIAL CONDITIONS

The sensitivity of our SCM to the initial conditions was examined by including randomly generated errors in the initial profiles of temperature (T) and specific humidity (q). A total of 50 model runs were performed using forcing data from the Summer 1995 IOP. Each model run utilized a slightly different set of initial conditions by including a random perturbation of $\pm 1.0^{\circ}\text{C}$ (T) and $\pm 5\%$ (q) in each model layer. The magnitude of the standard deviation of temperature generally increases as the model run progresses in time with a maximum value of approximately 4°K . Maximum values of the specific humidity standard deviation were 3.3 g kg^{-1} . Similar sets of perturbation runs have been performed using four other ARM IOP data sets (Fall 1994, Fall 1995, Spring 1996, and Summer 1997) and have in general yielded similar results.

The standard deviation of cloud fraction (σ_{cld}), cloud ice/water path (σ_{cwp}), downwelling surface shortwave radiation (σ_{sol}), and outgoing longwave radiation (σ_{olr}) from the 50 perturbation runs were also computed. Maximum values of σ_{cld} were approximately 0.30 while σ_{cwp} reached a maximum of 30 grams m^{-2} . Maximum values of σ_{sol} and σ_{olr} were 40 and 25 W m^{-2} , respectively. The magnitudes of both σ_{sol} and σ_{olr} indicate that small instrumental errors (represented here by the added perturbations) in the initial conditions may have a significant impact on the model produced radiative fluxes. These results suggest that when using the SCM in a sensitivity study or during parameterization development, an ensemble of model runs be performed, each run using a slightly perturbed initial profile of temperature and humidity.

SCM INTERCOMPARISON PROJECT

We participated in a comparison of SCM simulations of summertime midlatitude continental convection during the ARM 1995 Summer IOP. A total of eleven SCMs participated in the study and each model contained a unique combination of physical parameterizations. As a result of the comparison, some errors in the boundary conditions were identified by common signatures among the various models. Some of the differences between model results were identified as model problems and have led to corrections and/or improvements in individual models.

6. *Electronic figures with paragraph discussions highlighting current research.*

Somerville_SIO_2000_Cloud.doc

Somerville_SIO_2000_Vert.doc

Somerville_SIO_2000_Stoch.doc

7. *Refereed publications either submitted or published during the current grant FY that acknowledge DOE ARM support.*

Lane, D. E., R. C. J. Somerville, and S. F. Iacobellis, 2000: Sensitivity of cloud and radiation parameterizations to changes in vertical resolution. *Journal of Climate*, **13**, 915-922.

Iacobellis, S. F., and R. C. J. Somerville, 2000: Implications of microphysics for cloud-radiation parameterizations: Lessons from TOGA-COARE. *Journal of the Atmospheric Sciences*, **57**, 161-183.

Somerville, R. C. J., 2000: Using single-column models to improve cloud-radiation parameterizations. *General Circulation Model Development: Past, Present and Future*, Academic Press, in press.

Ghan, S. J., D. Randall, K. Xu, R. Cederwall, D. Cripe, J. Hack, S. Iacobellis, S. Klein, S. Krueger, U. Lohmann, J. Pedretti, A. Robock, L. Rotsteyn, R. Somerville, G. Stenchikov, Y. Sud, G. Walker, S. Xie, J. Yio, and M. Zhang, 2000: A comparison of single-column model simulations of Summertime midlatitude continental convection. *Journal of Geophysical Research, D. (Atmospheres)*, **105** (D2), 2091-2124.

8. *Published (either paper or web-based) extended abstracts and other non-refereed publications in the current FY that acknowledge DOE ARM support*

Somerville, R. C. J., S. F. Iacobellis, and D. E. Lane, 1999: Testing cloud-radiation scheme with single-column models and ARM observations. *Proceedings of the Ninth Atmospheric Radiation Measurement (ARM) Science Team Meeting*, March 22-26, 1999, San Antonio, TX, pp. 1-4. (Electronic Publication).

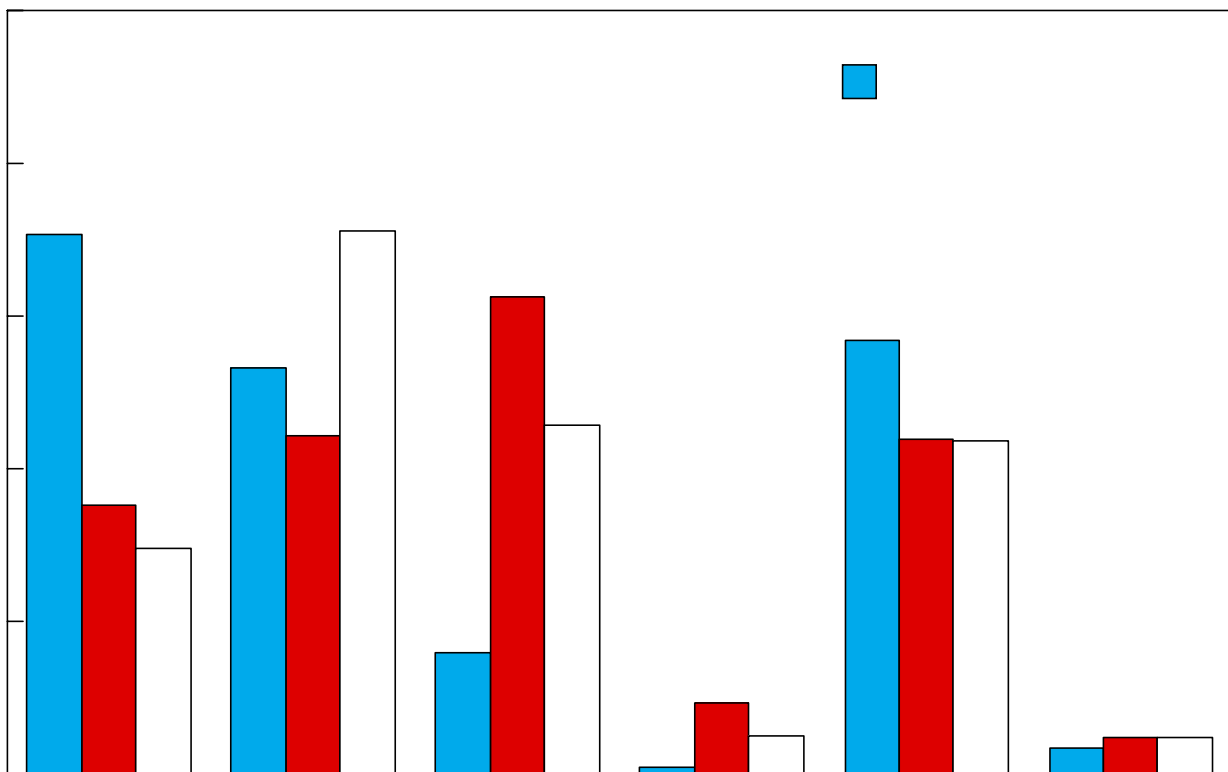
Goris, K. J., 1999: A characterization of clouds at the ARM southern Great Plains site based on ground instrumentation data. M.S. thesis, Dept. of Earth Sciences, University of California, San Diego, xi+44 pp. [Available from University Microfilm, 305 N. Zeeb Rd., Ann Arbor, MI 48106.]

Lane, D. E., 2000: Stochastic theory and cloud-radiation interactions. Ph.D. dissertation, Scripps Institution of Oceanography, University of California, San Diego, xxiv+169 pp. [Available from University Microfilm, 305 N. Zeeb Rd., Ann Arbor, MI 48106.]

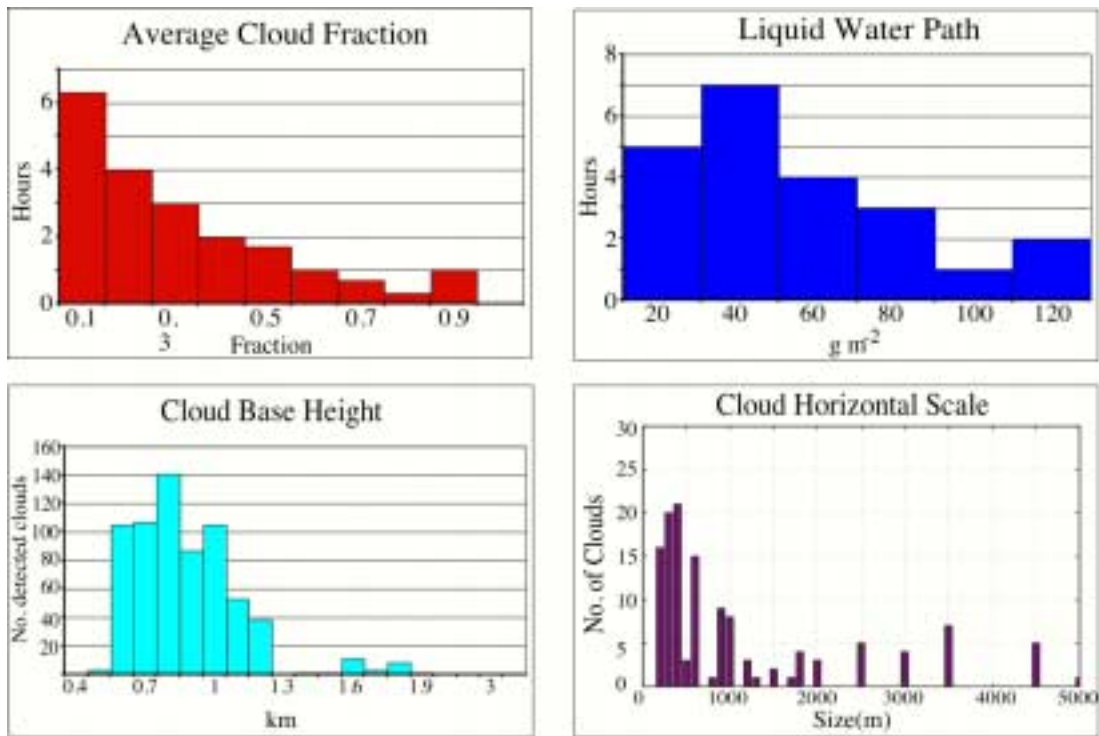
- Iacobellis, S. F., R. C. J. Somerville, and D. E. Lane, 2000: Evaluation of cloud-radiation sensitivities to alternative cloud and convection schemes. *Preprint from the Eleventh Symposium on Global Change Studies*, American Meteorological Society, January 9-14, 2000, Long Beach, CA, 328-331.
- Lane, D. E., R. C. J. Somerville, and S. F. Iacobellis, 2000: Validation of a stochastic radiative transfer model. *Preprint from the Eleventh Symposium on Global Change Studies*, American Meteorological Society, January 9-14, 2000, Long Beach, CA, 336-339.
- Iacobellis, S. F., R. C. J. Somerville, and D. E. Lane, 2000: Analysis of forcing methods for single-column models. *Preprint from the Eleventh Symposium on Global Change Studies*, American Meteorological Society, January 9-14, 2000, Long Beach, CA, 340-343.
- Iacobellis, S. F., R. C. J. Somerville, and D. E. Lane, 2000: SCM sensitivity to microphysics, radiation and convection algorithms. *Proceedings of the Tenth Atmospheric Radiation Measurement (ARM) Science Team Meeting*, March 13-17, 2000, San Antonio, TX, pp. 1-6. (Electronic Publication).
- Lane, D. E., R. C. J. Somerville, and S. F. Iacobellis, 2000: Evaluation of a stochastic radiative transfer model using ground-based measurements. *Proceedings of the Tenth Atmospheric Radiation Measurement (ARM) Science Team Meeting*, March 13-17, 2000, San Antonio, TX, pp. 1-4. (Electronic Publication).

9. *Status of submitted referred publications from the previous FY progress report.*

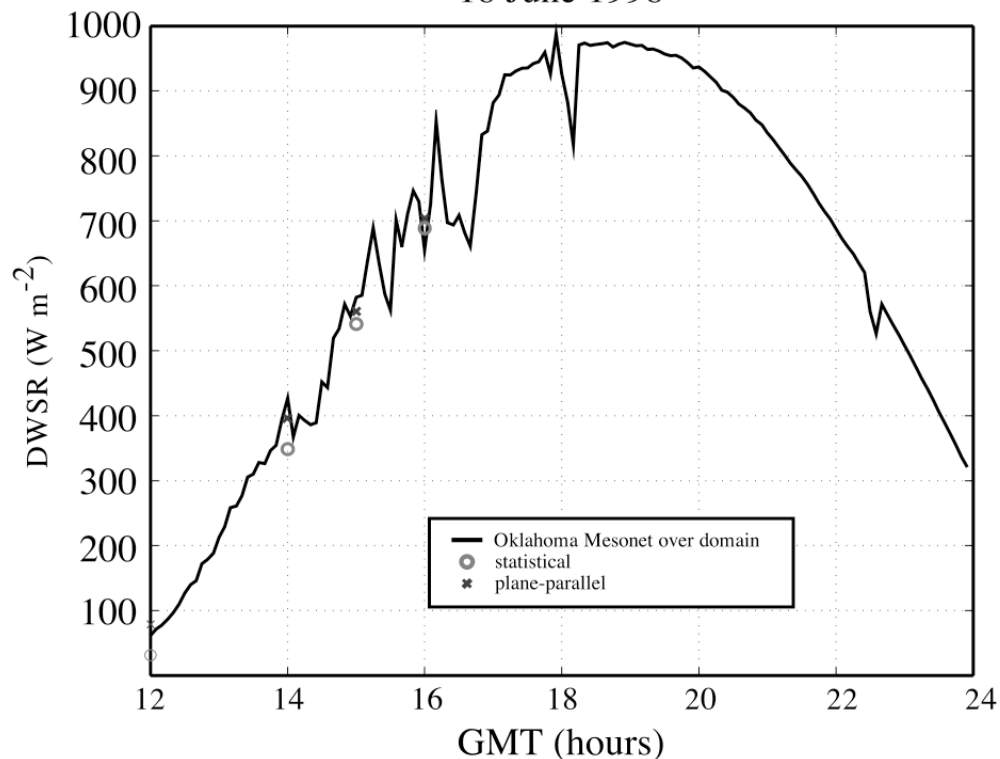
NONE



Percentage of occurrence of various cloud types from two SCM runs and from satellite measurements. SCM run NOCW used a diagnostic cloud parameterization and run CWRI used a prognostic cloud/cloud water scheme. The most realistic vertical distribution of clouds was obtained from the SCM experiment that included the most complete representation of cloud microphysics
Richard Somerville, Scripps Institution of Oceanography, UCSD, 2000

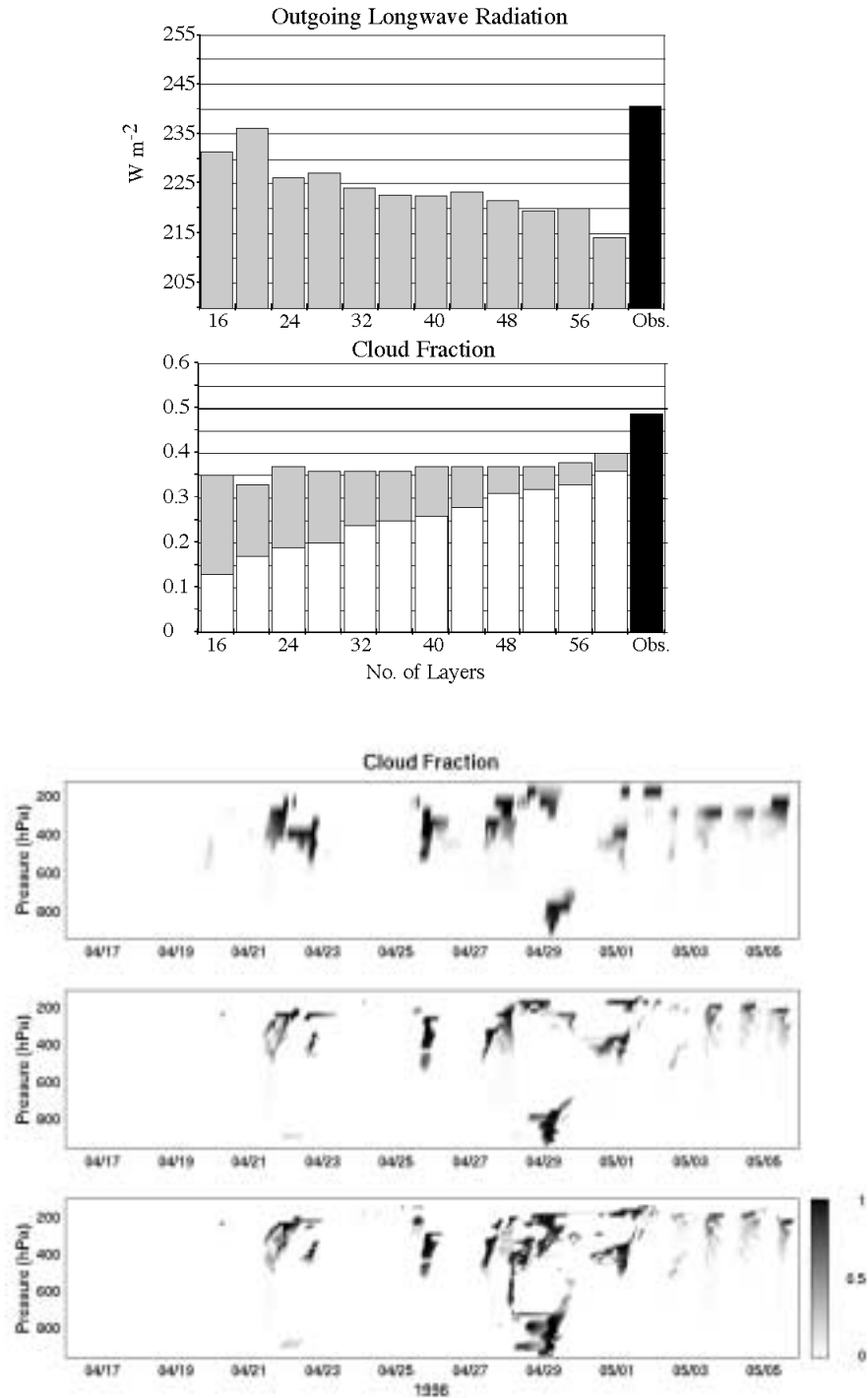


18 June 1998



Top four panels show the characterization of low-lying fair weather cumulus fields at the SGP. Bottom panel illustrates a comparison between the two models and observations for 18 June 1998, for the four hours that the scattered clouds were present.

Richard Somerville, Scripps Institution of Oceanography, UCSD, 2000



Results from the vertical resolution experiment for the Spring 1996 IOP. Top two panels indicate that there is no 'ideal' resolution indicated. Bottom panel shows the profile of cloud fraction for 16, 40 and 60 layers. The variations in the cloud profile indicate the strong response of the SCM convective processes to the resolution change.

Richard Somerville, Scripps Institution of Oceanography, UCSD, 2000